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An innovative method and apparatus for speed control of pipe health monitoring robot during gas pipeline inspection

Kanhaiya Lal Chaurasiya[a], Varun Pawar[a], and Bishakh Bhattacharya[a]

[a]Indian Institute of Technology Kanpur, Uttar Pradesh, India

ABSTRACT

Periodic pigging of pipelines is essential for the inspection and maintenance of the gas pipeline network. Undetected cracks can be detrimental to pipelines and can often compromise the integrity of the pipeline. Pigging operation requires the pipeline inspection gauges to move at a moderately low yet uniform speed to inspect the defects, including corrosion, cracks, and deposits, developed in the pipeline after prolonged service. The speed of the pipe health monitoring robot (PHMR) can attain an undesirable high magnitude due to fluctuations in pressurized gas flow conditions prevailing in the pipelines. The high travel speed results in aliasing, leading to a consistent sampling of error-prone inspection data. The present study explores and expands on the previous speed control units by developing an innovative method of a novel speed control system based on the combination of deflector bypass flow and hydraulic brake mechanisms and experimentally validating it for PHMR. The speed control system developed is highly responsive to the changes in the speed of the PHMR since the incompressible nature of the brake fluid makes instantaneous transmission of pressure changes for the braking action possible. The modular nature of the developed speed control system enables it to be attached to any wheel suspension assembly-based PHMR and has been reported to passively regulate any undesirable high-speed spikes maximum by 51% within the acceptable range. The system is operated without a power supply, making it highly safe while operating in inflammable gas pipelines and a cost-effective and reliable solution that can help in accurate, effective, and seamless inspection of the gas pipelines spread over a large area of the pipeline network.

Keywords: Speed control system, Pipeline Inspection, Brake unit, Pigging, Health monitoring, Hydro-mechanical unit, Bypass flow

1. INTRODUCTION

Pipelines are commonly used throughout the world for transporting natural gas, crude oil, and other refined products over a long distance. After a prolonged service, pipelines start to develop defects, including corrosion, cracks, and deposits.[1,2] Therefore, the integrity of the pipeline has to be inspected periodically to ensure the healthy life and transportation capacity of the pipeline network remain intact.[3,4] Currently, pigging is one of the most effective ways to assess the health of the pipeline.[5,6] In general terms, the pigging process involves the inspection of the pipeline network by inserting a pipe inspection tool followed by scanning for defects as it travels into the pipeline. The inline inspection tool can be broadly categorized into a blocked flow-based conventional pipeline inspection gauge (PIG) and a bypass flow-based next-generation pipe health monitoring robot (PHMR). Unlike a conventional PIG, the novel PHMR is a lightweight inspection vehicle, and it does not hinder the regular transportation of natural gas through the pipelines during the inspection operation due to its inherent bypass flow characteristics. The driving principle involves the flowing gas exerting drag force on the system along with the existing pressure gradient between the two sides of the apparatus, which in effect, moves the inspection tool in a pipeline. The conventional PIG and the PHMR also differ in their design and support system - the former system has a sliding contact with the pipeline inner surface because of the sealing cups or disc-based design of PIG, while the latter maintains a rolling contact using a wheel suspension assembly to reduce the possibility of the stick-slip condition, thus eliminating the negative impact of dry-friction induced chatter vibration on the

Further author information: (Send correspondence to B.B.)

K.L.C.: E-mail: kanhaiya@iitk.ac.in

V.P.: E-mail: varunpwr897@gmail.com

B.B.: E-mail: bishakh@iitk.ac.in

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integrity of the gas pipelines.[7,8] The novel PHMR is equipped with non-destructive inspection systems such as magnetic flux leakage (MFL) sensors, piezo-electric based touch probes (PZT), and optical detection system consisting of infrared transmitters and receivers.[9–11] While traveling along the pipeline, inspection data are collected and then collated for post-processing and analysis at the end of the pigging operation.

The accuracy of data acquisition by an inspection tool is severely affected when the travel speed of the system exceeds the scanning rate of the sensing device on board. Therefore, it is necessary to attach a speed control module that regulates the speed and the stability of the PHMR to ensure the proper functioning of the inspection tool during pigging in the gas pipeline. In a recent development, a speed control unit based on spherical cups or disc-based system for conventional Pipeline Inspection Gauge (PIG) has been developed, which adjusts the bypass cross-sectional area depending upon the fluid flow rate and the pressure differential between the nose and tail sides of the PIG.[12–15] The system requires an additional electronic system to regulate the bypass valve in this active control device, depending on the travel speed. Moreover, the electronic system suffers from an inherent minimum response time, and when a sudden spike in the speed of PHMR occurs, the system cannot respond in due time, which leads to inaccuracies in the inspection and data acquisition of pipeline defects.

In one of the reported speed control mechanisms, the approach adopted is to control the speed of PIG by way of externally generated controls such as controlling the flow rate or operating pressure, which would result in an increase or decrease in the speed of the PIG.[16,17] Many active and passive speed control techniques have been used in conventional pigging systems. In the passive speed control mechanisms, the approach follows the control of the PIG speed through mechanical operations that do not require an external or additional power supply. On the other hand, in active speed control, the PIG travelling speed in the pipeline is regulated by the corresponding embodied mechanisms driven by the electrical energy. The use of a bypass valve is a commonly deployed active speed control mechanism wherein the valves are actuated using a solenoid element. The solenoid valves require power supply; hence, the PIG cannot be used for long runs due to the onboard battery power limitation. The hydraulic actuators, by virtue of their robustness, harness the rotational energy transmitted from the wheels to actuate the valve; hence they are generally preferred in modern PIG designs.

A literature survey[18–20] shows that very few papers deal with the design and simulation of passive speed control systems for wheel suspension assembly-based next-generation pipe health monitoring robots. Numerical simulation of bypass speed control system designed for sealing cups or disc-based design of conventional PIG has been discussed in detail by various authors in an open literature.[21–24] The present work is thus focused on the design and study of a speed control system for PHMR wherein bypass flow and hydraulic mechanism work in tandem to control the speed of the inspection tool. The current study highlights the novel design and discusses the development of a working prototype of the speed control system for PHMR with experimental validation, wherein hydraulic brakes are applied on the wheels proportional to the speed of the inspection tool. Therefore, the system is designed to control the speed of the PHMR during the pigging operation.

2. METHODOLOGY

2.1 Gas flow simulation

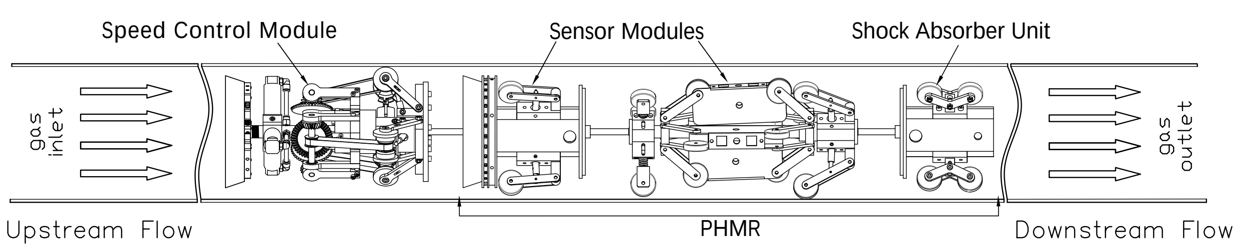


Figure 1: Schematic of pipe health monitoring robot (PHMR) having sensor modules and shock absorber unit integrated with a speed control module in a natural gas pipeline. The fluid flow field has been decoupled into the upstream and downstream flows about the robot.

Fluid flow simulation in a gas pipeline follows the computational scheme wherein the flow field is decoupled into the upstream and downstream flows about the robot as shown in the Figure 1. The robot moves forward due to the pressure difference between the tail and nose and the drag force exerted by the flowing fluid on the system. At the same time, the motion of the robot also affects the flow field nearby. In the fluid flow model, the following assumptions have been made,[25]

1. Natural gas behaves as an ideal gas. There is no phase change happening during the flow through the pipeline.
2. The pipe center-line is nearly horizontal to neglect the gravitational effects.
3. The pipe diameter does not change over the length, and the thickness of the pipe is adequately large to neglect radial deformations.
4. The heat flow from gas to the pipeline is assumed to be quasi-static.
5. The friction factor varies with Reynolds number and pipe surface roughness. The steady-state values are considered for calculations.

The continuity, momentum, ideal gas equation, and energy equations have been applied to the flow modeling as given in equation (1), (2), (3) and (4) respectively[26,27] and the flow variables P, ρ and u are solved at each PHMR location x and time t,

$$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + \rho\frac{\partial u}{\partial x} = 0 \tag{1}$$

$$\frac{\partial P}{\partial x} + \rho u\frac{\partial u}{\partial x} + \rho\frac{\partial u}{\partial t} + \frac{F_f}{A} = 0 \tag{2}$$

$$\frac{P}{\rho} = RT = (\gamma - 1)C_v T \tag{3}$$

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{u^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\rho u\left(e + \frac{u^2}{2}\right)\right] + \frac{\partial}{\partial x}(Pu) - \frac{qS}{A} = 0 \tag{4}$$

where, P, ρ and T denote pressure, density and temperature in the flow field, respectively. C_v is specific heat at constant volume, γ is adiabatic constant of the fluid, and F_f is the frictional force per unit length. A and S represent the cross-sectional area and circumferential perimeter of the pipe, respectively. The flow variables u, ρ and P are calculated at each location x and time t.

2.2 Mechanism of speed control system

The primary function of the brake unit is to control the spikes in the travel speed to obtain accurate inspection data by the PHMR. The rolling of the brake wheel on the inner surface of the pipeline is enabled by pressing the wheel against the wall using the spring-based suspension mechanism. The brake wheel transmits its kinetic energy to the piston-cylinder sub-assembly using a gear train system. The centrifugal force on the piston is used to build up the pressure in the hydraulic system. The pressurized brake fluid pushes the brake shoe and establishes an additional normal force on the brake wheel. This instantaneously causes an increase in the magnitude of the frictional force between the brake wheel and the pipeline inner surface, which in turn slows down the PHMR. The frictional force at the brake wheel also decreases its rotational kinetic energy, thus lowering the brake fluid pressure. Subsequently, the springs in the brake shoe and piston-cylinder sub-assemblies restore the system to its initial state. The hydro-mechanical solution discussed is highly responsive to the sudden changes in the travel speed of the PHMR since the incompressible brake fluid enables instantaneous pressure transmission to the hydraulic braking unit. The closed-loop control system depicting the above sequential steps is shown in the Figure 2.

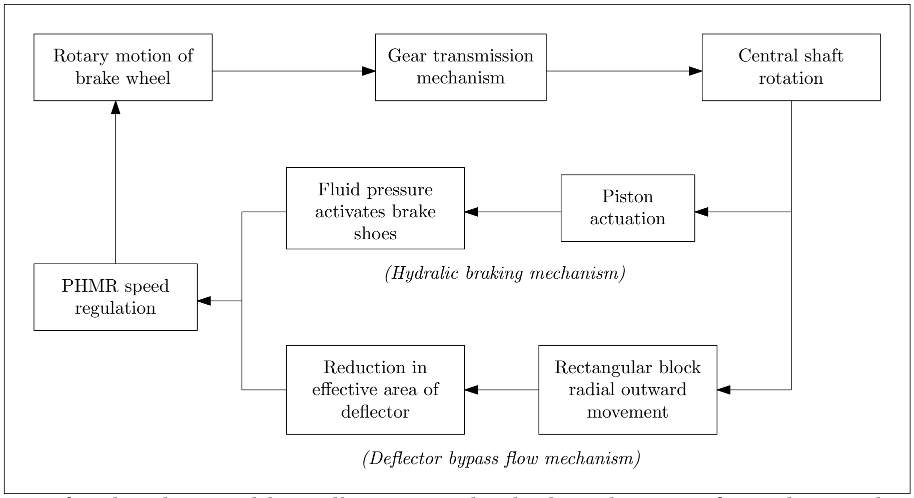


Figure 2: Schematic of a closed control loop illustrating the dual mechanism of speed control system - hydraulic braking and deflector bypass flow mechanisms regulating the speed of the pipe health monitoring robot.

2.3 Prototyping and experimentation

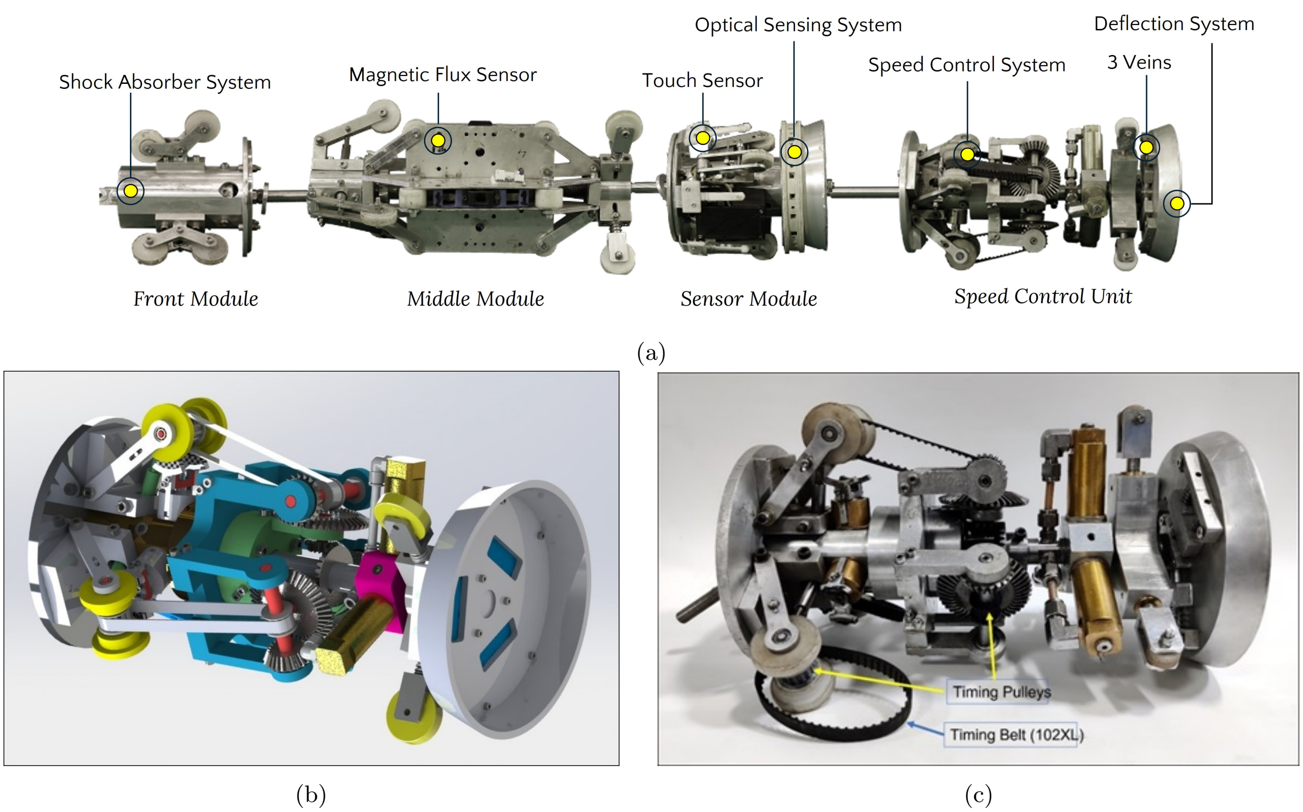


Figure 3: (a) Full assembly of pipe health monitoring robot (PHMR) integrated with speed control unit showcasing the front module, which consists of a shock absorber system; the middle module with magnetic flux leakage sensors and, the sensor module, which houses piezo-electric based touch probes and optical sensors, position tracer (rotary encoder), DC power supply for electronics system onboard, and a data acquisition unit(b) Isometric view of the CAD model of the speed control system, (c) shows the fabricated prototype of the speed control unit.

The pipe health monitoring robot system primarily comprises three modules and a speed control unit: the front module, which consists of a suspension system to absorb any sudden impact on the system; the middle module has magnetic flux leakage sensors installed for defect detection, the sensor module, which houses piezo-electric based touch probes and optical sensors, position tracer (rotary encoder), DC power supply for electronics system onboard, and a data acquisition unit as shown in Figure 3a. The speed control prototype has been developed for PHMR operational for an eight-inch (8") diameter pipeline, considering the design calculation and parameter optimization based on mathematical modeling. Figure 3b and 3c illustrate the CAD model and physical prototype of the speed control system for a PHMR. Each module has been designed to keep maneuverability throughout and is interconnected with other units through a ball and socket joint.[28] The design of PHMR has wheel suspension sub-assemblies compared to the spherical disc or cup-based conventional PIG. Therefore, it is easily slid into the launcher point of the pipeline using a custom-made trolley launcher arrangement.

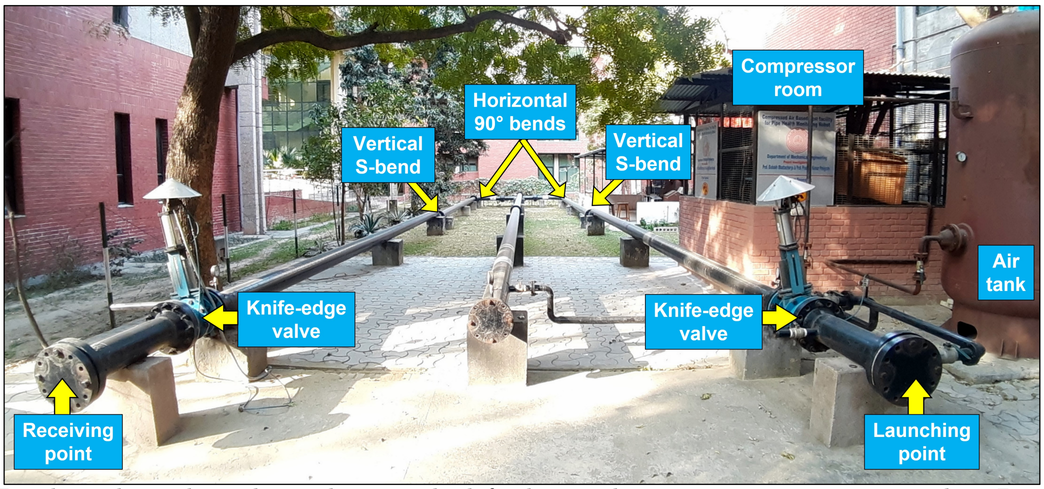
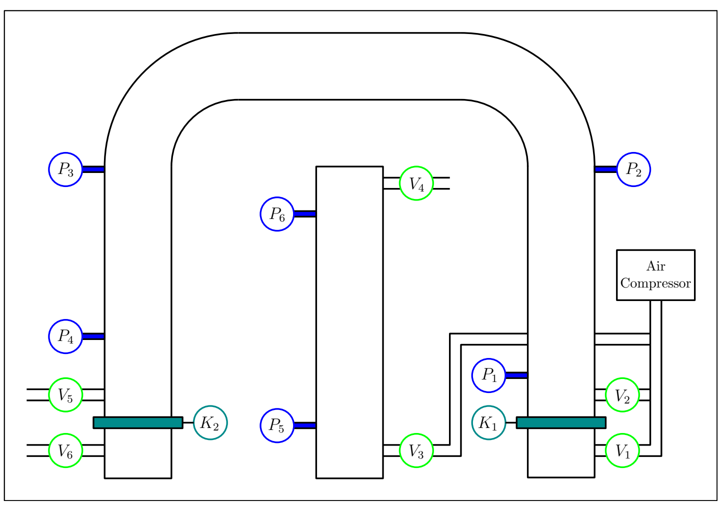


Figure 4: Displays the eight-inch pipeline test-bed facility with air compressor operational at Department of Mechanical Engineering, IIT Kanpur, India. The test-bed houses two horizontal 90° elbow and vertical S-bend sections in the complex pipeline to perform maneuverability checks of the modular blocks of the PHMR.



(a)

Component	Description
K_{1-2}	Knife-edge valves
P_{1-6}	Pressure gauge points
V_{1-3}	Airflow inlet valves
V_{4-6}	Airflow outlet valves

(b)

Parameter	Value
Compressor type	GA22VSD+ FF
Maximum pressure	12.75 bar
Output flow-rate	75.1 L/s
Voltage	400 V
Frequency	50 Hz
P motor	22 kW
N motor	5700 rpm

(c)

Figure 5: (a) schematic diagram of the pipeline test-bed automation with key components including an air compressor, launching and receiving points, pressure gauge positions, and air-flow and knife-edge valves, (b) and (c) tabulate the description of the key components of pipeline test-bed and technical parameters of the air compressor respectively.

A pipeline test-bed of 60 m with a pipe diameter of eight-inch with an air compressor under a maximum pressure capacity of 12.75 bar is operational at the Department of Mechanical Engineering, IIT Kanpur, India, as shown in Figure 4. The test bed (30 $m \times 7$ m) consists U-shape complex pipe section with launching and receiving points, pressure gauge positions, and air-flow and knife-edge valves as indicated in Figure 5a and 5b. The technical parameters of the air compressor system are listed in Figure 5c. The complex pipe section (60 m) consists of two horizontal 90° elbows and two vertical S-bends, which provide a testing platform to check the maneuverability of the inspection tool.

The objectives of the experiment include validation of the functioning of the speed control system in regulating the velocity of the PHMR and the maneuverability check of the modular blocks of the PHMR in the complex pipe section of the pipeline test-bed. The experimental pressure condition involves setting the inlet pressure at 3.2 bar using an air compressor and maintaining atmospheric pressure at the pipe outlet. The speed of the system is being measured with the help of a magnetic-based rotary encoder installed on the wheels of the PHMR.

3. RESULT AND DISCUSSION

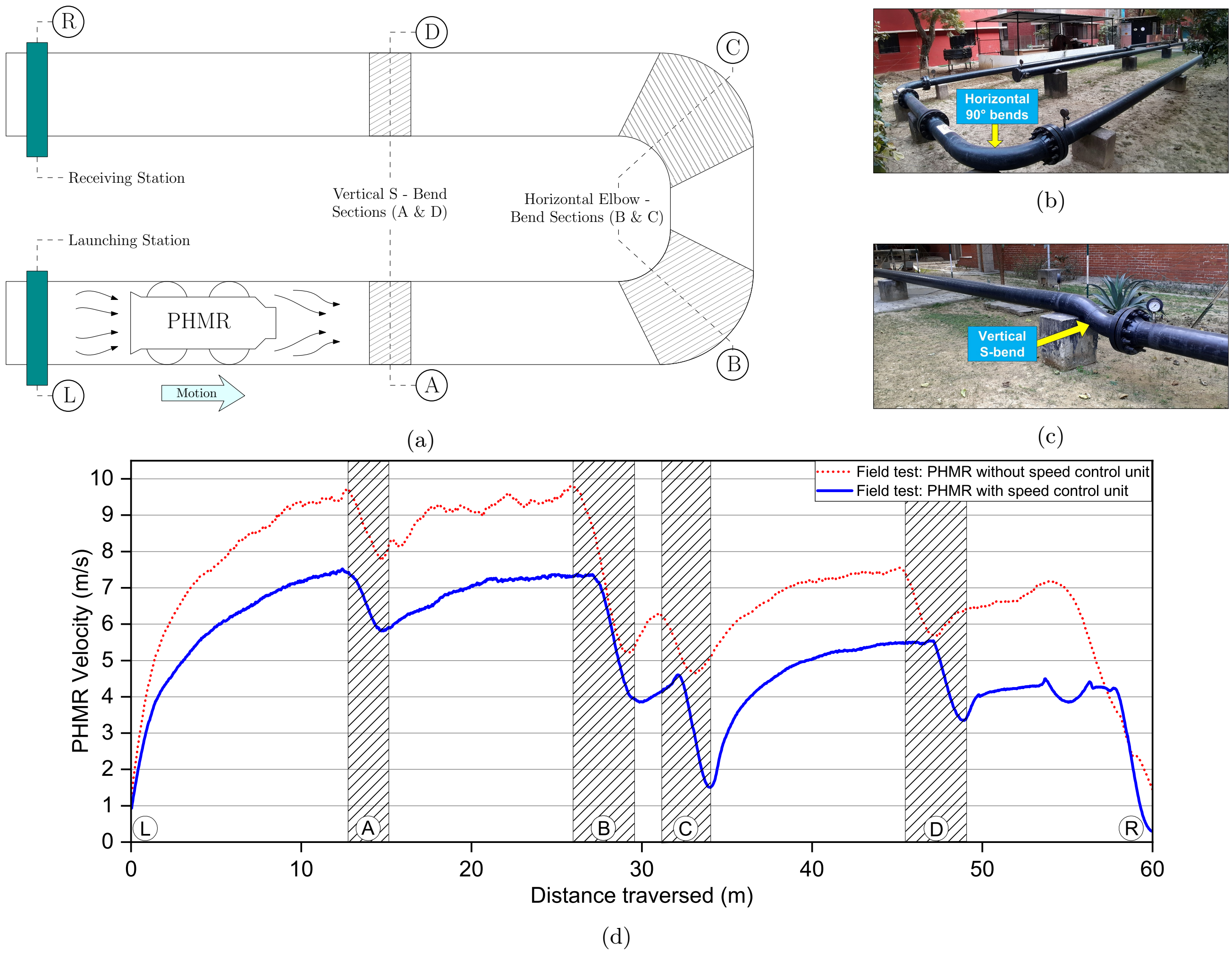


Figure 6: (a) shows the schematic diagram of the 60 m complex pipeline test-bed with PHMR for experimentation validation, (b) and (c) showcase the vertical S-bends and horizontal 90° elbow bends used for checking the maneuverability and agility of the PHMR. (d) presents the experimental result of the velocity profile of the PHMR with and without the speed control system for an inlet fluid pressure of 3.2 bar. The maximum and average velocity reductions are 51% and 27% with respect to the case when the PHMR is coupled with the speed control system.

4. CONCLUSION

This paper presented an innovative speed control system for a pipe health monitoring robot to improve the effectiveness of inspection tool during pipeline pigging. The speed control system is one of the most crucial units of the inspection tool as it facilitates slower travel of PHMR, resulting in improved detection, identification, and classification of the defects and crack-like anomalies on the pipeline wall. The novel feature of the system is that its design offers the dual integration of bypass leakage flow and hydro-mechanical brake mechanisms. This integration makes the system versatile and more responsive to the sudden change in the travel speed of the PHMR. Designed with relatively fewer elements, this system offers reliability and stability of all the sub-components under high-pressure conditions ($\sim$10 bar) while reducing the operation and maintenance cost of the brake unit. The speed control prototype was fabricated, and field tests were conducted to measure the impact on the speed of the PHMR coupled with the speed control system.

The current research work is partially motivated by the increasing demand from the global pipeline monitoring systems industry and presents a novel speed control system for next-generation wheel suspension-based PHMR as an alternative to sealing cups or disc-based systems of conventional PIG. The developed system is a passive, robust, and lightweight hydro-mechanical system that can be customized in line with the desired magnitude of travel velocity, making it distinguishable from the existing speed control units. The current system design has a provision for bypass flow; thus, it does not create hindrances in the normal delivery or halt the transportation operation of natural gas through the pipelines during inspection service. The entire system does not require any electrically powered motors, and hence it is safe and robust for driving pipe inspection robots at a relatively slower speed in an inflammable environment.

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